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OPTIMIZATION OF TOOL WEAR DURING PLUNGE TURNING OF HARDENED 18CrMo4 STEEL

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Summary

The paper investigates the influence of cutting parameters (v_c, f, m) on the tool wear VB_B during finish plunge hard turning of hardened 18CrMo4 steel with the use of Cubical Boron Nitride (CBN) inserts. The experimental research was conducted according to the Taguchi methodology. On the basis of the research results obtained, optimal values of cutting parameters were determined, for which the tool wear VB_B is minimal. Next, the analysis of variance ANOVA was performed in order to determine the significance of the impact of particular cutting parameters on the optimized criteria. Verification tests which were carried out confirm the conclusions drawn that the greatest influence on tool wear VB_B has the cutting speed v_c which should be the lowest and feed f which should be the lowest too.

Keywords: plunge hard turning, tool wear, optimization, Taguchi method

Optymalizacja zużycia narzędzia podczas wgłębnego toczenia zahartowanej stali 18CrMo4

Streszczenie

W pracy przedstawiono wpływ parametrów skrawania (v_c, f, m) na zużycie narzędzia (VB_B) podczas wykończeniowego wgłębnego toczenia na twardo stali 18CrMo4 w stanie zahartowanym płytkami z regularnego azotku boru (CBN). Badania eksperymentalne prowadzono z uwzględnieniem metodyki Taguchi'ego. Analiza uzyskanych wyników badań była podstawą do wyznaczenia optymalnych wartości parametrów skrawania, dla przyjętego kryterium najmniejszego zużycie narzędzia. Wykonano również analizę wariancji ANOVA w celu określenia istotności wpływu poszczególnych parametrów skrawania na optymalizowane kryterium. Wyniki przeprowadzonych badań weryfikujących potwierdziły, że największy wpływ na zużycie narzędzia ma prędkość skrawania. Dlatego należy stosować najmniejsze wartości prędkości skrawania, również posuw powinien mieć wartość minimalną.

Słowa kluczowe: wgłębne toczenie na twardo, zużycie narzędzia, optymalizacja, metoda Taguchi'ego

1. Introduction

The increase in popularity of hard turning in recent years has brought many interesting variations of this machining method [1]. One of them is hard turning with plunge feed. The most important advantage of this machining method is the reduction of machining time of approx. 75-90% as compared to straight hard turning, even using the Wiper geometry inserts. This is a significant advantage in the current pressure to reducing the manufacturing time and production costs.

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Another advantage of hard turning with plunge feed is distribution of the cutting process over a considerable length of the cutting edge of the insert, which in combination with the short contact time of the stock with the tool results in extension of the tool life [2, 3]. Other benefits include the elimination of coolant and helical machining marks. Of course, hard turning with plunge feed has several drawbacks. The main one is the occurrence of increased cutting forces resulting from the distribution of the cutting process over a considerable length of the cutting edge. In addition, the quality of the finish, as well as the strength of the cutting edge of the insert must be high [2]. Also, high costs of Cubical Boron Nitride (CBN) tools should be mentioned, as a result, it is essential that tool wear should be limited to a minimum.

The width of the machined surface during plunge turning is limited to the length of the cutting edge of the insert. However, if the machining surfaces mating with sealing rings (Simmerring ring), this restriction is not an obstacle, because the contact of the sealing ring with the shaft surface occurs on a very small width. The results of preliminary research presented in paper [4] indicate that the surface of the steel 18CrMo4 after plunge hard turning perfectly meets the requirements for suitable geometrically-dimensional accuracy and surface layer properties [5-7]. Chromium-manganese steel 18CrMo4 for carburizing, hardening and tempering is a common material for gear parts, for example for toothed shafts cooperating with the sealing rings. So far, the most common in industrial practice as finishing operation of surfaces mating with the sealing rings is used plunge grinding with a sufficiently long time of sparking-out, recommended by most manufacturers sealing rings. The problem of alternative methods of finishing surfaces mating with the sealing rings was raised, among others in the papers [8-10].

2. Methodology

The paper investigates the influence of the cutting speed v_c, plunge feed f and displacement m on the criteria tool wear VB_B. The average width value of flank wear VB_B measurements were performed during the research. The displacement parameter m consists in a small movement of the insert along its cutting edge, the purpose of which is the elimination of the effects of profile roughness of the cutting edge on the machined surface [2]. It occurs after the completion of the plunge feed movement of the cutting insert. The displacement values m were assumed on the basis of research of the roughness profile of the flank face along the cutting edge (Fig. 1) carried by the gauge MahrSurf WS 1.

The experimental study was performed with the use of the Taguchi methodology. This methodology allows a simple, efficient, and systematic improvement of product quality and/or a reduction of its machining costs by using experimental research. Traditional designs of the experiment are complicated and difficult to use. Additionally, when the number of input parameters increases

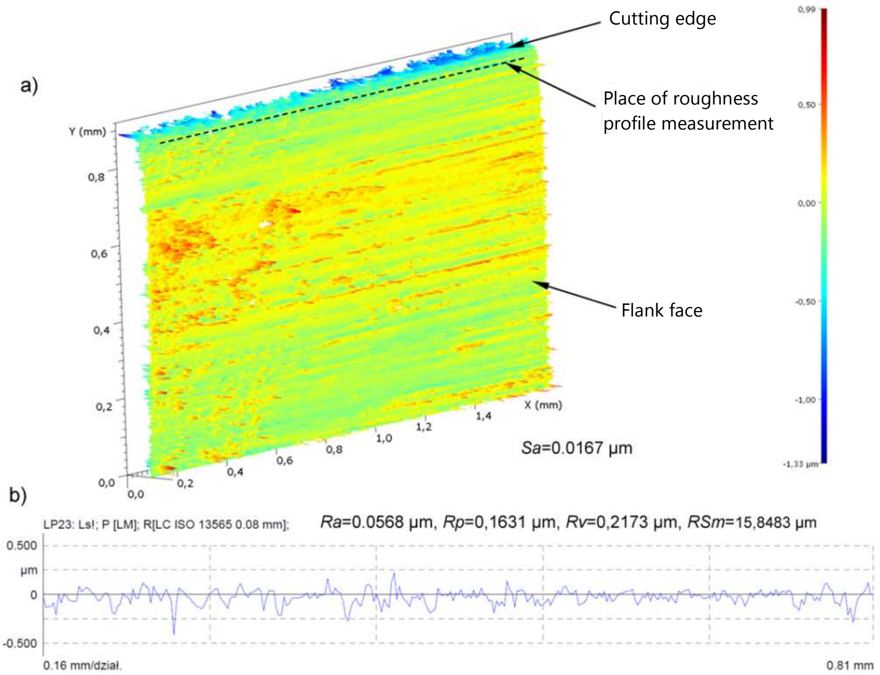

Fig. 1. Topography of flank face (a) and roughness profile measured along the cutting edge with selected surface roughness parameters (b)

it is necessary to perform a large number of experiments [11]. Orthogonal arrays designed by Taguchi allow for simultaneous and independent assessment of the influence of two or more input parameters on the output parameter when the minimal number of experiments is performed. In the Taguchi methodology, the lost function is defined which is the difference between the desired value and the experimental value. In turn, the lost function can be transformed to the signal-to-noise *S/N* ratio, which, depending on the characteristic of the examined quantity can be: the smaller-the better, the bigger-the better, and the nominal-the better. Values of the signal-to-noise *S/N* ratio for the tool wear VB_B were calculated adopting the smaller the better criterion (SB), with the use of the following equation :

$$S/N_{SB} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where: n – number of the measurements for a given layout of the experimental design, y_i – measured value of the investigated parameter. Regardless of the type of the optimized size, the largest value of the *S/N* coefficient corresponds to the optimal levels of the cutting parameters.

Three setting values of the cutting parameters were used in the experimental research v_c = 100, 200, 300 m/min, f = 0.02, 0.04, 0.06 mm/rev and m = 0, 0.025, 0.05 mm, successively referred to as level 1, 2 and 3. The experimental research was conducted according to the experimental design based on the orthogonal array L_9 (Table 1). For each layout of the experimental design 3 repetitions were performed. During the research, the following initial levels of the cutting parameter are assumed v_c = 200 m/min, f = 0,02 mm/rev, m = 0.025 mm labeled as: v_c2, $f1$, $m2$.

Table 1. Setting levels and the corresponding values of the cutting parameters for particular layouts of the experimental design based on the orthogonal array L_9

Layout No.	Level			Cutting parameters		
	v_c	**f**	**m**	**v_c, m/min**	**f, mm/rev**	**m, mm**
1	v_c1	$f1$	$m1$	100	0.02	0
2	v_c1	$f2$	$m2$	100	0.04	0.025
3	v_c1	$f3$	$m3$	100	0.06	0.05
4	v_c2	$f1$	$m2$	200	0.02	0.025
5	v_c2	$f2$	$m3$	200	0.04	0.05
6	v_c2	$f3$	$m1$	200	0.06	0
7	v_c3	$f1$	$m3$	300	0.02	0.05
8	v_c3	$f2$	$m1$	300	0.04	0
9	v_c3	$f3$	$m2$	300	0.06	0.025

For each attempt at a final stage of the machining, a dwell is performed which is equal to two shaft rotations, aimed at assuring adequate dimensional accuracy of the machined surface. The research was conducted on the shaft having dimensions of Ø60×300 mm, made from 18CrMo4 steel. 27 grooves were cut on the shaft with dimensions of 4×4 mm, which created 27 cylindrical surfaces with the width 6 mm (9 layouts of the design × 3 repetitions), used in the course of the research. In the next step, the shaft underwent the following thermo-chemical treatments: carburizing to the depth of 2 mm, hardening and tempering to the hardness of 60±2HRC. The machining was carried out on the CNC lathe TUG 56-MN. Monolithic inserts TNGX1103085S-R-WZ of CBN100 grade which consisted of 50% CBN (grain size 2 µm) and 50% TiC used as the binder were used for finishing hard turning. The inserts were clamped in the tool holder CTJNR 2525 M11. During the research, a 0.2 mm-thick layer of the material was removed for each attempt.

The tool wear measurements were carried out on an optical microscope ZKM 01-250C. The wear values were measured each time after the execution of 20 attempts with 3 repetitions. The total number of attempts for the tool wear was 200. Statistical analysis of the results was performed using the software package Statistica v.12.

3. Results and their analysis

The measured values (mean from 3 repetition) of the average width of the flank wear VB_B and the corresponding S/N_{SB} after plunge turning are given in Table 2.

Table 3 and Figure 2 present the mean value of the ratio S/N_{SB} for each set-up level for the average width of flank wear VB_B.

Table 2. The values of the average width flank wear VB_B and the corresponding S/N_{SB}

Layout No.	**VB_B, μm**	**S/N_{SB}, dB**
1	127.7	-42.133
2	144.3	-43.200
3	144.7	-43.213
4	146.1	-43.291
5	155.7	-43.861
6	163.9	-44.291
7	160.7	-44.128
8	171.2	-44.675
9	189.1	-45.536

Table 3. The mean values of the S/N_{SB} ratio for the average width of flank wear VB_B

Cutting parameter	**Mean value S/N_{SB}, dB**			**$S/N_{SB\,max} - S/N_{SB\,min}$**
	level 1	**level 2**	**level 3**	
v_c, m/min	-42.848	-43.814	-44.780	1.931
f, mm/rev	-43.184	-43.912	-44.347	1.163
m, mm	-43.699	-44.009	-43.734	0.310
Total mean ratio η = -43.814 dB; ▨ – optimal level				

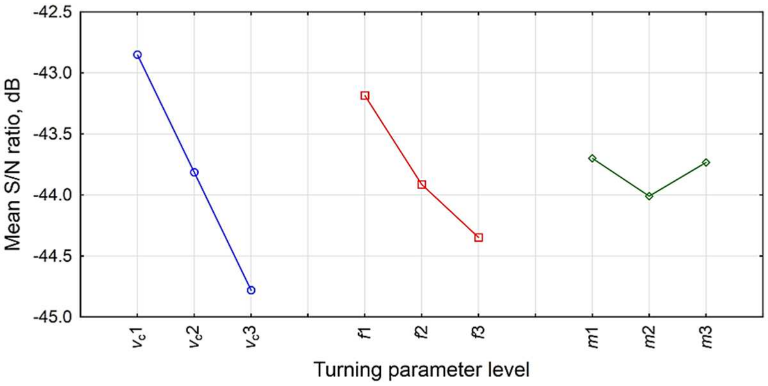

Fig. 2. The graph of mean values of the S/N_{SB} ratio for the average width of flank wear VB_B

An analysis of Table 3 and Figure 2 shows that the optimal levels of cutting parameters (the highest values of S/N_{SB}) are as follows: v_c1, $f1$, $m1$. The most significant effect on the tool wear described by the parameter VB_B has the cutting speed v_c and feed f. The effect of displacement m is practically negligible. The decrease in the cutting speed v_c and feed f extends the tool life.

Figure 3 presents an exemplary photo of the rake face and the flank face of a worn insert (200 attempts) using the optimal levels of cutting parameters v_c1, $f1$, $m1$. While Figure 4 shows an example of the relationship of tool wear VB_B as a function of the number of attempts made for the same level of cutting parameters. The tool wear process has linear character.

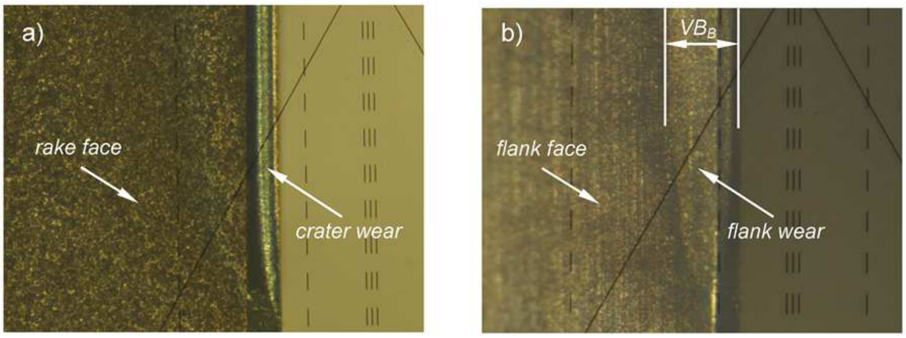

Fig. 3. Rake face with visible crater wear (a) and flank face with visible flank wear VB_B (b)

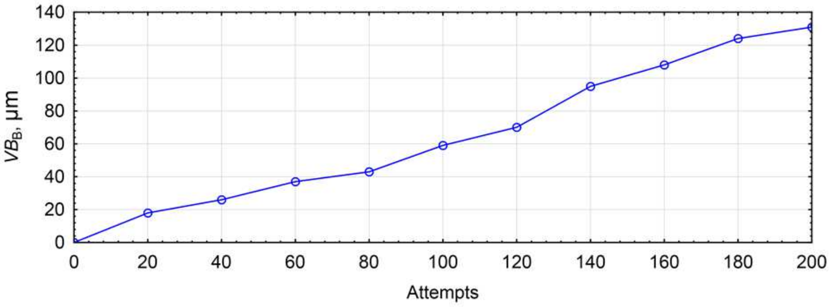

Fig. 4. Graph of the average width of flank wear to VB_B as a function of the number of attempts made

At the next stage of the research, analysis of variance ANOVA was performed to determine which particular cutting parameters v_c, f, m significantly influences the tool wear VB_B. The analysis was performed at the significance level of 1% (99% confidence level). The results of the ANOVA for the tool wear VB_B are given in Table 4.

Table 4. Results of the analysis of variance ANOVA for the value flank wear VB_B

Cutting parameter	**Degrees of fredom**	**Sum of squares**	**Mean square**	***F***	**Contribution, %**
v_c	2	5.594	2.797	155.138	71.04
f	2	2.072	1.036	57.450	26.31
m	2	0.173	0.086	4.792	2.19
Error	2	0.036	0.018	–	0.46
Total	8	7.875	–	–	100

Analysis of variance ANOVA for the tool wear VB_B indicates, that cutting speed v_c explain 71.04% of total variance tool wear, and the feed f – 26.31%.

After determining the optimal levels of the cutting parameters, in the next step, a verification experiment is performed that in a practical way confirms the improvement of the optimized criteria. For optimal values of cutting parameters due to the tool wear, the value of the *S/N* ratio was determined labeled as η_{opt} [12]:

$$\eta_{opt} = \eta + \sum_{i=1}^{n} \left(\eta_i - \eta \right) \tag{2}$$

where: η_i – value of the *S/N* ratio for the optimal level of the cutting parameter, i – number of parameters affecting the optimized criterion in a significant way.

Table 5 shows the results of the confirmation experiment using the optimal cutting parameters based on the tool wear criteria.

Table 5. The results of the confirmation experiment for the optimal values of the cutting parameters based on the criteria of tool wear

Parameters	**Initial cutting parameters**	**Optimal cutting parameters**	
		Prediction	**Experiment**
Level	v_c2, $f1$, $m2$	v_c1, $f1$, $m1$	v_c1, $f1$, $m1$
$F_{c\ avg}$, N	263	–	215
$F_{c\ max}$, N	397	–	415
$F_{f\ avg}$, N	543	–	508
$F_{f\ max}$, N	827	–	720
VB_B, µm	152	–	148
S/B ratio, *dB*	-43.637	-42.103	-43.405
Improvement of *S/B* ratio, *dB*	–	0.232	–

For the tool wear the improvement of the *S/N* ratio is low, 0.232 dB, which is only 5% decrease of the tool wear (Table 5). The optimal value of the cutting speed v_c for tool wear criteria is 100 m/min. But take into account the results of research from paper [13], as a final optimal cutting parameters values are proposed

$v_c = 300$ m/min, $f = 0.02$ mm/rev, $m = 0.025$ mm (v_c3, $f1$, $m2$), as this will allow the reduction of cutting forces. This, in turn, will provide more stable cutting conditions, minimizing the chance of vibrations, which have a very damaging effect on the CBN inserts, speeding up the cutting edge wear process in the form of micro-chipping (Fig. 5). Unfortunately, this disqualifies them from further machining of surfaces which are to be mated with the sealing rings. The proposed displacement level $m2$ has no significant impact on the value of tool wear, but it will make it possible to avoid the mapping of the above mentioned forms of wear on the machined surface.

Fig. 5. Characteristic cutting edge micro-chipping of CBN inserts

4. Conclusions

The paper presents the results of the optimization of cutting parameters due to the criteria of tool wear VB_B using the Taguchi methodology. This made it possible to reduce the number of experiments carried out to determine the optimal levels of cutting parameters (v_c, f, m). Summarizing the above results, the following conclusions can be drawn:

- On the basis of the mean value of the S/N ratio, the optimal levels are as follows: $_c1$, $f1$, $m1$ ($v_c = 100$ m/min, $f = 0.02$ mm/rev, $m = 0$ mm).
- On the basis of a subsequent analysis of variance ANOVA, it can be seen that the cutting speed v_c accounts for 71.04%, and the feed f – 26.31% of total variance of tool wear VB_B. Displacement m for tool wear has a practically negligible impact on these quantities.
- For optimal cutting parameter levels the results of the confirming experiments confirmed the above conclusions. It was possible to obtain the improvement tool life only at 5%.
- The proposed final optimal cutting parameters levels are as follows: v_c3, $f1$, $m2$ ($v_c = 300$ m/min, $f = 0.02$ mm/rev, $m = 0.025$ mm), they prefer the criteria of cutting forces [13] more than the criteria of tool wear. This is due to the need to ensure high process reliability because otherwise the process of accelerated tool wear occurs.

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